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STRIATION IN GAS DISCHARGE

by

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# HUMAN TRANSLATION

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| Block | Italic | Transliteration | Block | Italic | Transliteration |
|---|---|---|---|---|---|
| А а | *А а* | A, a | Р р | *Р р* | R, r |
| Б б | *Б б* | B, b | С с | *С с* | S, s |
| В в | *В в* | V, v | Т т | *Т т* | T, t |
| Г г | *Г г* | G, g | У у | *У у* | U, u |
| Д д | *Д д* | D, d | Ф ф | *Ф ф* | F, f |
| Е е | *Е е* | Ye, ye; E, e* | Х х | *Х х* | Kh, kh |
| Ж ж | *Ж ж* | Zh, zh | Ц ц | *Ц ц* | Ts, ts |
| З з | *З з* | Z, z | Ч ч | *Ч ч* | Ch, ch |
| И и | *И и* | I, i | Ш ш | *Ш ш* | Sh, sh |
| Й й | *Й й* | Y, y | Щ щ | *Щ щ* | Shch, shch |
| К к | *К к* | K, k | Ъ ъ | *Ъ ъ* | " |
| Л л | *Л л* | L, l | Ы ы | *Ы ы* | Y, y |
| М м | *М м* | M, m | Ь ь | *Ь ь* | ' |
| Н н | *Н н* | N, n | Э э | *Э э* | E, e |
| О о | *О о* | O, o | Ю ю | *Ю ю* | Yu, yu |
| П п | *П п* | P, p | Я я | *Я я* | Ya, ya |

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

## RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

| Russian | English | Russian | English | Russian | English |
|---|---|---|---|---|---|
| sin | sin | sh | sinh | arc sh | $\sinh^{-1}$ |
| cos | cos | ch | cosh | arc ch | $\cosh^{-1}$ |
| tg | tan | th | tanh | arc th | $\tanh^{-1}$ |
| ctg | cot | cth | coth | arc cth | $\coth^{-1}$ |
| sec | sec | sch | sech | arc sch | $\operatorname{sech}^{-1}$ |
| cosec | csc | csch | csch | arc csch | $\operatorname{csch}^{-1}$ |

| Russian | English |
|---|---|
| rot | curl |
| lg | log |

## GRAPHICS DISCLAIMER

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# STRIATION IN GAS DISCHARGE

B. N. Klyarfel'd

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The study of striation indicates that it forms at such pressures, at which there are at least ten collisions of the electron with gas molecules between heads of adjacent striae. At lower pressures, striae diffuse, and the column in all gases becomes uniform. With the exception of the range at such low pressures, the uniform column is comparatively rare and is observed primarily during discharge in Na-, Cs-, Cd- and Hg-vapors. The most common form of column is the layered; moreover, the presence of striae is usually masked by their rapid motion along the discharge. Striae are observed over a broad range of current density (in this work, to $j = 300$ A/cm$^3$), pressures and diameters of the glow discharge tube. A series of various tests demonstrates that pulsing and stationary striae have a common nature and are fundamentally similar. For instance, pulsing striae may be arrested, and stationary - set in motion. Both forms frequently can be observed at the same time. Pulsing striae exist not only in inert gases, but in a great number of other gases and metalloid vapors. The mechanism is examined by which consecutive striae are reproduced. It is shown that formation and annihilation of striation may be controlled by imposing different potentials on the probe in the column.

## 1. Introduction

The positive gas discharge column exists in two forms: a) uniform and b) striated. In the physical sense, the uniform column is the simplest discharge field. All characteristics of this simplest field may be calculated completely for low gas pressure from its atomic properties [1,2]. The other type of column - the striated column - is an incomparably more complicated phenomenon, which not only cannot now be fully calculated, but even the nature of which, in spite of voluminous work about the subject, is still not totally clear. A number of

researchers [3-6] has defined conditions in which striae appear, their dimensions and potential distribution within the limits of each stria. For instance, the striation is associated with the so-called minimum principle of gas discharge [4]. However, the specific formation mechanism of striation has yet to be discovered. In later attempts to identify the nature of striation [7,8], authors of these works, in most cases, originated from the following statements, which were considered sufficiently substantiated by experimentation: a) for striation to occur, a molecular gas is necessary, or at least molecular gas impurity, b) there are no stationary striae in inert gases; moving striae therein are of a nature other than stationary, and comprise a specific feature of discharge in inert gases; c) striation occurs only at low current density ($j < 10$ mA/cm$^2$) and at not very high pressures (on the order of several mm Hg); d) negative ions, as well as processes taking place on the walls of the discharge tube, play a major role in striation. Many experiments conducted in this work demonstrate that these statements are incorrect or, at least, are incomplete. Information gathered in this work may be expressed concisely with the following statements, which will be experimentally substantiated later on.

1. Any abrupt rise in potential under the influence of any factor in the gap between the cathode and anode, or a local increase of ion and electron concentration, is a site for stria generation. Ordinarily, such site is the field of cathode potential drop. Resulting striae occur at the anode side of the site of discharge disturbance. In certain cases, striae precisely recur the full length of a column, regardless of its length, and in others - dampen, converting to a uniform column.

2. Formation of each stria is dictated by processes which occur in the tail of the preceding (on the cathode side) stria.

3. Striae are stationary and pulsing. The latter may travel from the anode to the cathode, which happens in inert gases, or conversely, from the cathode to the anode, as was found in this

work in the case of hydrogen discharge. Stationary and pulsing striae are of the same nature and essentially the same. In fact, with outside influences on the discharge, stationary striation may be set in motion and, conversely, pulsing striation arrested. Hereinafter, we shall designate discharge as striated, regardless whether the striae are fixed, or traveling along the discharge[1].

4. Striation represents the most common form of positive column. It is observed at heavy current density (observations were made here to $j = 300$ A/cm$^2$) and at pressures above atmospheric. Well-formed striae were obtained in capillaries with 0.1 mm diameter. The uniform column, which can be observed with the unaided eye, in most cases is a layered column with pulsing striation.

5. The uniform column which exists at very low pressures in all gases without exception, at higher pressures is a comparatively rare form of positive column. It lies on the anode side of fading striation. The uniform column is observed in the case of discharge product in vapors of such metals as Na, Cs, Cd, Hg, and in inert gases containing minute hydrogen impurity. In case of other gas fillings, the column, in most instances, is layered its entire length.

6. The presence of negative ions, in addition to processes on the walls, are not the sole factors needed for stria formation. They are important only as factors causing the disappearance of charged particles in the gap between adjacent striae.

Accepting these statements already demands a new approach to explaining the mechanism of striation which is different from the one used earlier. Therefore, after offering experimental verification of these conclusions, a new attempt will be made to explain the nature of striation formation.

[1]Factors causing shift of striations were not studied here.

## 2. Description of Experimental Material

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1. When gauze, screen with an opening, or a probe is inserted into a uniform positive column, or even when the tube tapers or turns, invariably, striae form on the anode side of the site of the disturbance [9]. This phenomenon is observed to some degree in all tested gases, vapors of metals, metalloids and their mixtures. Figure 1 illustrates the positive column in neon with minute hydrogen content. (It was determined here that adding several percentages hydrogen eliminates pulsing striation in inert gases$_2$). If a screen with a small hole is placed in the path of discharge, then resulting striation is quickly extinguished, changing to a uniform column (fig. 1,c, inset in the original document). Space potential is imparted on thin probe, position of which between the screen and anode is noted with an arrow, in the case shown in fig. 1,c. In this instance, no striae form beyond the probe. If the probe is made to "float", i.e. is disconnected, and then is charged negatively at 10-20 V relative to the plasma, this causes (fig. 1,b) formation of extinguishing striae. If the discharge disturbance is amplified, having given the probe a negative potential of 300 V relative to the plasma (fig. 1,a), distinct extinguishing striae are already visible.

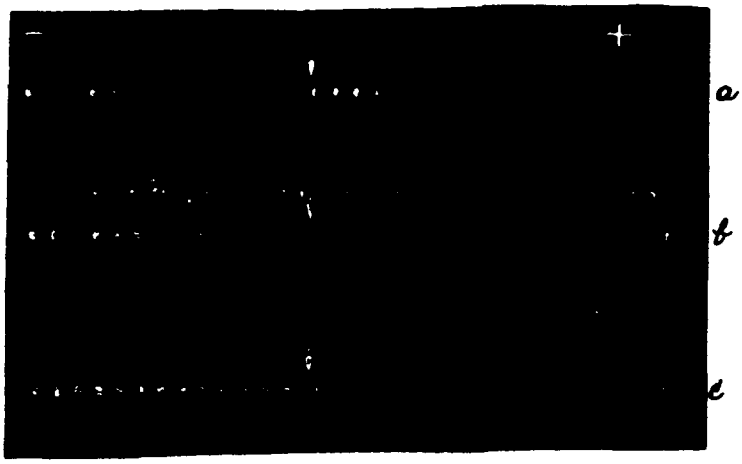


Fig. 1. Striation in discharge disturbance; a - probe at 300 V potential; b - probe disconnected; c - probe at plasma potential. Dark cross band at the left - screen with opening.

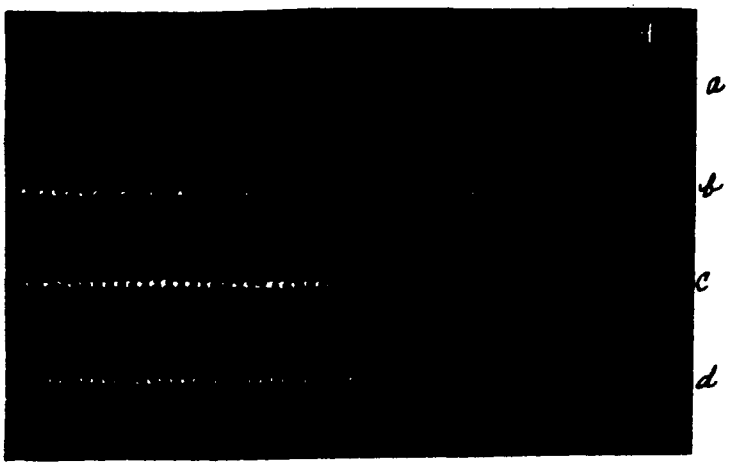


Fig. 2. Transition from extinguished to sustained striation as hydrogen content rises in neon and hydrogen mixture.

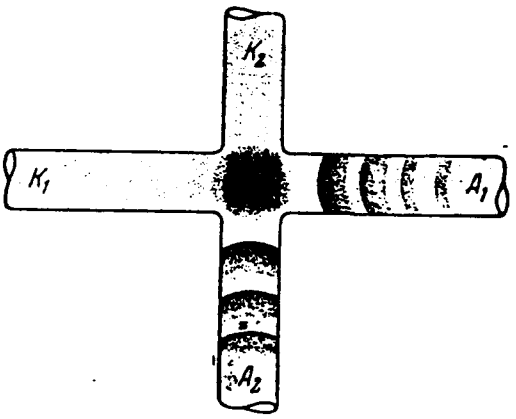


Fig. 3. Formation of stria beyond the site of high discharge intensity.

Figure 2 shows that, in cases of certain gas fillings, striation brought about by interference in the column, is rapidly extinguished, and in cases of others - are sustained for a large length of the tube. Discharge was produced in mixtures of neon with different percentages of hydrogen. Pressure of the blend was 0.3 mm, discharge current - 50 mA, column diameter -

[2] Column uniformity is checked by viewing it in a rotating mirror, or by amplifying photo currents from a photocell beyond the slot in the screen at right angles to the column axis. The amplified photo current is fed to oscillograph deflector plates.

20 mm. Striation was caused by placing a screen with an opening across the column. Figure 2,a shows a photo of a discharge column in a mixture of neon with minute level of hydrogen; in this case, striation is rapidly extinguished. Figures 2,b and 2,c illustrate the effect of raising the percentage of hydrogen; striation extinguishment is much weaker. Finally, in fig. 2,d, hydrogen content reaches 30%, and striation is practically sustained.

Local increase of ion and electron concentration in the column may be induced, having created additional cross discharge intersecting the main one. This can be achieved in a cruciform discharge tube (fig. 3), in which intersecting columns are supplied from sources not electrically connected. When the transverse discharge is turned on, on the anode side of the junction in the column, which up to this point was uniform, first there is a dark space, then striae. This phenomenon is shown in fig. 3.

2. The very existence of damping striae produces the thought that each stria is brought about by processes which take place in the tail of the preceding (on the cathode side) stria and change in intensity from stria to stria. This conclusion is even more obvious when we observe a long column with many tens of sustained striae while gas pressure in the column slowly rises. In this case, the first striae beyond the cathode drop field, remain almost stationary, and those removed from the cathode travel toward the cathode at speeds proportional to the space of the given stria from the primary one. This indicates that shortening the length of each stria causes shift of all the rest, i.e. all adjacent striae are joined by a direct bond.

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3. In observing discharge in different gases with the aid of a rotating mirror, one may find such discharge conditions in which several stationary layers follow on the anode side of the barrier which serves as the source of striation (fig. 4). Then vertical bands are replaced with stepped ones, indicating that for part of the time the striae are stationary, and the other

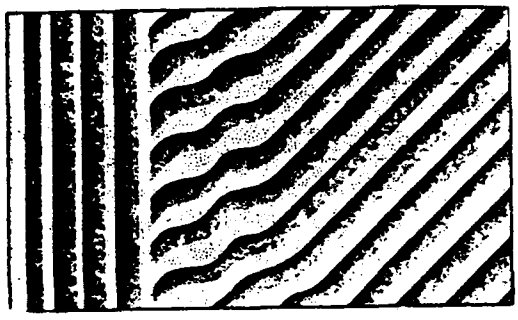

Fig. 4. Resolution of discharge with a rotating mirror. Left - stationary striae, right - pulsing.

part, quickly travel lengthwise along the column. Finally, at the farthest distance to the anode, oblique bands are visible, which corresponds to motion of striae along the column at uniform velocity. A similar pattern was observed with the most diverse gases, for example, He, Ne, Ar, $H_2$, $N_2$, and with mixed gases: He + $H_2$, Ne + $H_2$, Hg + $H_2$, and so on. Hence, it follows that since stationary and pulsing striae exist simultaneously in discharge, then their nature should be identical; at only one location are they fixed in space, and at the other, certain factors cause their shift. This is confirmed by results of measurements of potential U, electron concentration $n_e$ and their temperature $T_e$ about the discharge space in pulsing striae [10]. These figures vary from head to tail of each stria just as in stationary striae [8]. Whereas it was presumed before that pulsing layers are observed only in inert gases, in this work pulsing striae were also noted in hydrogen and in the narrow range of discharge conditions in $N_2$ and $O_2$. Here, in hydrogen, the layers moved not from the anode to the cathode, but from the cathode to the anode. Other factors refuting common opinion that pulsing striae are a specific phenomenon typical only of inert gases, are tests to artificially arrest pulsing striae, or to set stationary striae in motion. Striae may be arrested by placing a length of a neon column in a uniform transverse magnetic field with strength on the order of 100-200 Oe. Tube diameter in these tests was 30 mm,

neon pressure - 0.3-0.5 mm, discharge current - from 0.1 to 0.5 A. Another method of arresting striae in inert gases involves placing a series of probes in the discharge tube at a distance from one another on the order of tube diameter. In conditions when the space between probes is close to length of the stria, and when a potential is imposed on the probes on the order of hundreds of volts negative relative to the plasma, striae are arrested. Stationary striation in hydrogen may be set in motion by means of a local transverse magnetic field. All listed tests surely point to a commonness of nature of stationary and pulsing striation.

4. Observations of the column with the aid of a rotating mirror demonstrated that the layered column is the most common state of positive glow. In hydrogen, for example, the layered column is observed even at such low current density as $10^{-5}$ A/cm$^2$. On the other hand, using quartz tubes with a middle capillary section with diameter of 0.2 mm, striae may be clearly observed under a microscope at current density above 300 A/cm$^2$. In this case, hydrogen pressure was 100 mm Hg. Thus, invariably, striae were observed in hydrogen while current density changed by nearly eight orders of magnitude.

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The lower margin of pressures at which striae still exist in hydrogen in the case of tube diameters of 20-30 mm, is pressure on the order of 0.1 mm. This pressure corresponds to electron free path lengths comprising approximately 0.1 times the distance between heads of adjacent striae. When pressure drops, striae diffuse and become difficult to observe. Such a situation occurs in all gases and vapors[3]. As pressure rises, striae in hydrogen were observed right up to pressure above atmospheric. These observations were made in capillaries with diameter of

[3] Vlasov developed a theory of striation based on consideration of interaction of electrons removed from one another, as well as close [11]. This theory disregards collisions of electrons with molecules. Since striae exist only when tens of electron free path lengths are contained between adjacent stria heads, consequently, Vlasov's theory cannot be drawn in to explain the nature of striation in the positive column.

0.15-0.2 mm under a microscope at 40X magnification. Space between adjacent striae, which were stationary and clearly outlined, was nearly 0.04 mm here. Thus, layered discharge may be observed as pressure changes by a factor of $10^4$. There is no doubt that striae may occur at even higher current densities and pressures. It is also probable that the range of tube diameters at which layered discharge is possible is also wide. In [12], striae are obtained in tubes with 150 mm diameter[4]. Striation was observed in this work in capillaries with diameter of 0.1 mm.

5. The uniform column is observed in those cases when striae excited near the cathode are extinguished, converting to uniform glow. Studies indicated that this takes place in discharges in Hg, Cs, Na and Cd vapors, and in mixtures of these vapors with minute quantity of inert gases. There is no striation in pure mercury vapors in the wide range of pressures from 0.001 mm to thousands of mm. Comparing atomic properties of gases and vapors with one another, in which a uniform column is observed, it is noted that in the most number of cases, virtual profiles of atoms of these substances for collisions with electrons decreases sharply as electron velocity increases.

6. The existence of layered discharge in quite pure inert gases: He, Ne, Ar, Kr and Xe, in which formation of negative ions is unlikely, serves as refutation of the frequently held opinion that formation of striae is dictated by the presence of negative ions in the discharge. The same may be said about the role of processes on the walls of the glow tube. If we were to select conditions such that recombination of ions and electrons occurring on the walls of the tube was replaced by recombination in space, then there would be no need for walls. Figure 5 illustrates layered discharge in a blend of hydrogen and water vapors. Here, space between adjacent striae is only 1/20 the diameter of the column, and, naturally, processes on the walls are not the reason for striation here.

[4]At great diameter and pressure, it is hard to see striae since they become fine and irregular, and their motion is erratic.


Fig. 5. Striae in a blend of hydrogen with water vapor. Space between striae is 1/20 the column diameter. Pressure 0.4 mm; current intensity 20 mA; column diameter 60 mm.

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3. Mechanism of Stria Formation

The layered column is a collection of current-permeated plasmas separated from one another by potential differences - dual charge layers. In the head of each stria is intense ionization and excitation of gas by electrons accelerated in the layer on the cathodic side of the stria. Electron velocities, concentrations of charged particles and intensity of glow discharge are the highest here. Away from the stria head, all these values steadily diminish, and in the tail of the stria, discharge current is transferred by slow electrons diffusing through the dark gas space from their high concentration field. To explain the mechanism of stria formation, we must first respond to the following three questions.

1. Why, when a potential drop occurs in a discharge for whatever reason, on the anode side of this drop is there a field with charge particle concentration exceeding their concentration in the uniform column.

2. Why, after steady decrease of charged particle concentration in departure from the site of the initial potential difference, a new potential jump occurs at some distance from it.

3. Why, in certain cases, the new potential jump precisely reproduces the previous, and sustained striae occur, and in other cases, the new jump is much less than the preceding, and striae are extinguished toward the anode side.

Qualitative responses to all questions are the following:

1. If in the discharge, potential jump separates two adjacent plasmas: plasma I and plasma II, then this means that the boundary of plasma I from its anodic side as if plays the role of the cathode emitting electrons into plasma II. Current

here is limited to negative space charge, and dU/dx should equal zero. The potential jump between plasma is automatically established at such a level so as to provide by intense ionization within the confines of plasma II, a value of ionic current directed toward plasma I at which dU/dx at the anodic side of the double layer also drops to zero. The theory of double layers, without regard to collision within the bounds of the layer, or the initial of initial velocities of charged particles, produces for the relation of directed ionic current to electronic in the layer, the value $\sqrt{m_e/m_p}$, where $m_e$ - mass of the electron, and $m_p$ - mass of the positive ion. Complete solution of this problem leads to the expression for $I_p$ - ionic current: $I_p = I_e C_1 \sqrt{m_e/m_p}$ [13]; moreover, $C_1$ in conditions in which striae exist, may be appreciably different from one, to the side of larger values.

In the uniform positive column, however, when $\text{lambda}_e$ and $\text{lambda}_p$ are much smaller than column diameter, the relation of ionic and electronic currents directed to opposite sides is equal to the relation of their mobilities:

$$\frac{I_p}{I_e} = \frac{(e\lambda_p / m_p \bar{c}_p)\sqrt{(m_p + M)/m_p}}{e\lambda_e / m_e \bar{c}_e},$$

where M - mass of the molecule. Hence

$$I_p = I_e \frac{\lambda_p}{\lambda_e}\sqrt{\frac{2T_e}{T_p}}\sqrt{\frac{m_e}{m_p}} = I_e C_2 \sqrt{\frac{m_e}{m_p}}; \quad (1)$$

here $C_2$ ordinarily, is less than one.

When a layer is joined with the column, ionic current in the layer should be equivalent to ionic current at the origin of plasma II. Since $C_1 > C_2$, this is possible only when concentration of charged particles on the anode side of the layer is several times the concentration in the uniform column[5]. /72

[5] For very low pressures, when $\text{lambda}_e > d$, the ratio of ionic current to electronic in the uniform column is much less than the relation $\sqrt{m_e/m_p}$ [14]. Thus, here too, when a double layer occurs, there should also be a higher concentration of charged particles in the field behind it.

This issue may also be studied from the point of view of the minimum principle. If certain factors leads to a potential jump $U_0$, then an increase of the value $U_0$ will cause an increase in the number of ionizations in plasma II approximately according to an exponential law (see calculations given below). But, a greater number of ionizations will lead to higher concentration of charged particles, and thus, will cause diminution of the longitudinal field in the range behind the jump, and equilibrium is established when the sum of $U_0$ plus the potential drop within the confines of plasma II takes the least value. It is easy to see that this is the case when concentration in plasma II is much higher as compared with the uniform column.

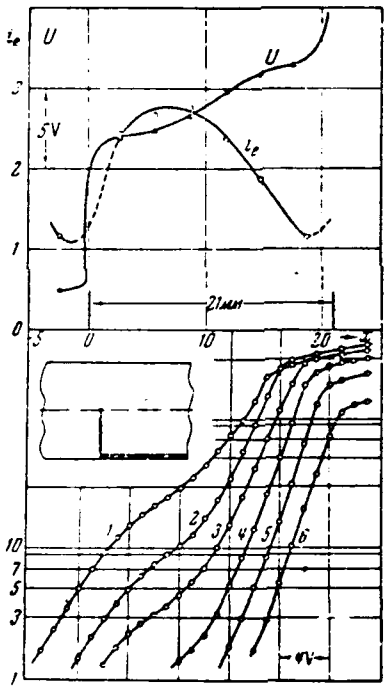


Fig. 6. Sounding characteristics taken at various distances x from the stria head. Top curves - disordered electron current density $i_e$ and potential U versus x. x is equal to: 1 - 3;, 2 - 6; 3 - 9; 4 - 12; 5 - 15; 6 - 18 mm.

2. The second question has already been studied in the work of Sobolev et al. [15]. Depending on distance from the head of the stria, high-speed electrons which have traversed the potential jump $U_0$, lose their velocity as a result of inelastic collisions, and ionization by electron collisions is all the rarer. A field originates in which positive ions and electrons are present primarily due to diffusion from the head of the stria. Here, discharge current is basically a diffuse stream of electrons toward the anode side brought about by a drop in their concentration. The reason for this is the decline the concentration of positive ions, which are as if the skeleton of the plasma. Ion concentration diminishes as a result of recombination on the walls or within the gas volume.

All this is well illustrated by the results of probe readings in striae (fig. 6), taken in a mixture 50% $H_2$ + 50% He with gross pressure 1 mm Hg. Discharge current was equal to 0.2 A, column diameter - 32 mm. The gaseous mixture used yielded consistently stationary sustained striae with no appreciable oscillations of any sort ordinarily observed in discharge [16]. The spherical probe, capable of traveling along the discharge, had diameter of 1.3 mm. With the aid of such a probe, comparatively reliable separation of ionic current form electronic was possible with little influence of the probe itself on the discharge. Arrangement of the probe in the discharge tube is shown separately in fig. 6.

Sounding curves given in fig. 6 for distances from the stria head of 3, 6, 9, 12, 15 and 18 mm, indicate the gradual disappearance of a cluster of high speed electrons. Distribution in the stria head was of Maxwellian character. /73

The density of the disordered electronic current $i_e$ approximately proportion to electron concentration, at first increases abruptly in the head of the stria, then decreases toward its tail. Path of the potential U indicates in this case the positive value dU/dx in the gap between adjacent potential jumps. In general, for discharge current practically equal to

the directed electronic current, the following expression holds:

$$i = eN_e\left(b_eE - \frac{D_e}{N_e}\frac{dN_e}{dx}\right). \qquad (2)$$

Here $N_e$ - number of electrons per 1 cm column length, $b_e$ - electron mobility, $D_e$ - electron diffusion coefficient, E - longitudinal electric field.

In case of a large relative value of electron diffusion flow, i.e. a large value of the second member in parentheses in expression (2), E not only decreases, but in appropriate conditions, may take a negative value. Negative value E was observed repeatedly in this work.

A decrease of the value $N_e$ which takes place at a distance form the head of the stria, has its own limit. To wit, there exists some value $N_e$, below which at given current and given $T_e$, this magnitude cannot fall. This value $N_{min}$ is defined by the expression:

$$N_{min} = \frac{I}{e}\sqrt{\frac{kT_e}{2\pi m_e}}. \qquad (3)$$

When $N_e$ in the tail of the stria, decreasing steadily, reaches the value $N_{min}$, further decrease is possible only in case of electron acceleration in the field of a new potential jump. The mechanism itself of the formation of a new potential jump may be represented as follows. Because of the lack of positive ions, electron space charge transferring discharge current to the anode, is not completely equalized. This means that $d^2U/dx^2$ has

[6] Two more remarks must be made concerning expression (3): 1) In a layer with thickness of approximately $lambda_e$ lying ahead of the new potential jump, $N_e$ is almost half of $N_{min}$. This occurs as a result of the disappearance of electrons with velocity components directed at the cathode. In striation conditions, due to smallness of $lambda_e$, this effect is difficult to detect with probes. However, at quite low pressures, such a drop of $N_e$ was observed in earlier work of the author and Sobolev [15] (see fig. 4 of the cited work). 2) In general, a second member should be included in expression (3), caused by the irregularity of electron concentration along the column. This circumstance, however, does not fundamentally alter the fact, especially as the influence of this member in case of an inverted field is largely neutralized.

a positive sign, and since dU/dx at the boundary of the resulting layer is close to null, then U begins to increase toward the anode.

Thus, the appearance in the column of a field with high value $N_e$, will lead first to attenuation or even reversal of sign of the longitudinal electric field, and second, after the drop in $N_e$ caused by this, to the appearance of a new potential jump at some distance [7].

3. The answer to the third question may be found by studying the dependence of ionizing capacity of a stream of electrons traveling through the accelerating field between adjacent plasmas, on the value $T_e$ in the tail of the same plasma from which the electrons exited (i.e. it is assumed here that, electrons in the tail of the stria have Maxwellian distribution). To balance space charges, it is necessary that enough positive ions be generated in the second plasma as needed to provide ionic current equal to the $\sqrt{m_e/m_p}$-fraction of the electronic. Since kinetic energy of electrons within the second plasma, is equal to their energy in the first plasma plus the energy acquired in traversing the potential jump, then for a determined number of ionizations produced in the second plasma, magnitude of the potential jump $U_0$ will be a function of $T_e$ at the boundary of the first plasma. Let's calculate the function $V_0$ versus $T_e$.

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[7] Distance from the stria head at which a new potential jump occurs, depends primarily on rate of charged particle concentration drop. Two marginal cases can be pointed out: a) Discharge in pure inert gases: He, Ne, Ar, Kr and Xe, at comparatively low pressure. Because of the lack of negative ions and, thus, low probability of recombination in the volume, andalso due to initiated column contraction shortening the distance of charged particles to the walls, ion and electron concentration diminishes slowly along the column, and between adjacent striae (pulsing), distance reaches a value many times the column diameter. Dark space between striae here may be an order of magnitude longer than the glow band. b) Discharge in the presence of water vapor shown in fig. 5. Intense recombination in the gas volume results in such a contraction of distance between striae that it is equal to 0.05 d.

Furthermore, the calculation method itself will differ from calculation of ionization which occurs in the positive column [1,2].

Distribution of electrons by energies U in their flux F escaping the space where electrons have Maxwellian distribution has the appearance:

$$\frac{dF_U}{F} = \frac{e^2}{k^2 T_e^2} U \varepsilon^{-Ue/kT_e} dU. \tag{4}$$

After traversing the accelerating potential difference, energy distribution in the electron flow takes the form:

$$\frac{dF_U}{F} = \frac{e^2}{k^2 T_e^2} \varepsilon^{-e(U-U_0)/kT_e} (U - U_0) dU. \tag{5}$$

In the case of striae, for which electron energy barely exceeds $U_i$, we assume that each electron will generate either one excitation or one ionization. Here, we disregard those energy losses which occur in elastic collisions. In fact, comparing virtual profiles for ionizing and exciting collisions with virtual profiles for elastic collisions, it is obvious that each ionization or excitation takes place over several elastic collisions with gas molecules, and elastic losses of electron energy in this case will be negligible. If Psi(U) - the relation of the number of ionizing collisions to the number of all inelastic collisions, which is a function of U, then for the number of ionizations $n_i$ due to each electron, we obtain the expression

$$dn_i = \frac{e^2}{k^2 T_e^2} e^{-e(U-U_0)/kT_e} (U - U_0) \Psi(U) dU. \tag{6}$$

The function Psi(U) was determined experimentally for Ar [17] and Hg [18]. It is shown in fig. 7. These functions agree well with the approximation:

$$\Psi(U) = A e^{-B(U-U_i)}, \tag{7}$$

furthermore, for Ar: A = 0.65; B = 0.55; for Hg: A = 0.45; B = 0.15. Figure 7 gives a comparison of experimental curves with their approximation, shown as a thin line.

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Integrating equation (6) for $n_i$ gives

$$n_i = A\frac{e^2}{k^2T_e^2}e^{-e(U_i-U_0)/kT_e}\left\{\frac{k^2T_e^2}{e^2}-\left(\frac{e}{kT_e}+B\right)^{-2}+\right.$$
$$\left.+\left[\frac{kT_e}{e}-\left(\frac{e}{kT_e}+B\right)^{-1}\right](U_i-U_0)\right\}. \qquad (8)$$

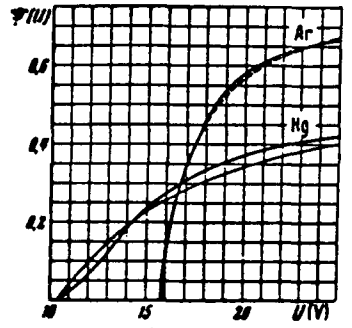


Fig. 7. Approximation for mercury and argon of the ratio of number of ionizing collisions to gross number of inelastic collisions of electrons versus energy. The thin solid line approximates Hg; dotted - Ar.

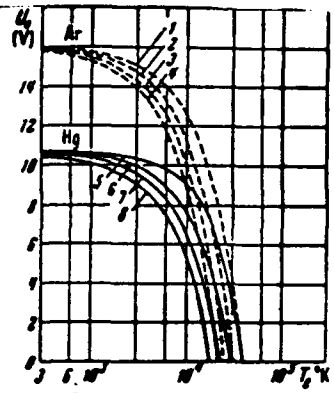


Fig. 8. $U_0$ versus $T_e$ at various $n_i$ - average number of ionizations produced by each electron within a stria. $n_i$ equals: 1, 5 - 0.03; 2, 6 - 0.01; 3, 7 - 0.003; 4, 8 - 0.001.

Calculated curves of $U_0$ versus $T_e$ for different values $n_i$ - numbers of ionizations generated on the average by each electron traveling from one stria to another, is given in fig. 8. These curves illustrate that, while $T_e$ does not exceed some value, $U_0$ depends little on $T_e$ and holds on near the value of the ionization potential. Upon further increase of $T_e$, the value $U_0$ quickly drops. Thus, a large $T_e$ in the stria tail causes the potential jump in front of the head of the next stria to decrease.

The magnitude $T_e$ in the tail of each stria defines the level $U_0$ ahead of the head of the next stria. If $T_e$ is small enough, then $U_0$ again takes the value of the preceding potential jump, and striae become sustaining. If $T_e$ in front of the site of the new jump remains high, then the new potential jump becomes less than the preceding, and the space of the jump itself becomes larger. Consequently, striae gradually diffuse and are

extinguished. Figure 9 shows a photo of discharge in a blend of 80% He and 20% $H_2$, produced in a tube with diameter of 32 mm at pressure 1 mm Hg and current 200 mA[8]. The values $T_e$ in front of heads of individual striae are listed in Table 1. These values were measured by the sliding spherical probe depicted in fig. 6. / 74


Fig. 9. Damping striae in a mix of 0.2 mm $H_2$ and 0.8 mm He. Column diameter 32 mm, current strength 200 mA. Electron temperatures in front of heads of individual striae are listed in Table 1. Striation source - screen with opening.

One can see from Table 1 how $T_e$ decreases from stria to stria. $U_0$ decreases simultaneously. The last point is already in the uniform column.

Table 1

| Stria number in sequence | 1 | 2 | 3 | 4 | Site corresponding to 10th stria |
|---|---|---|---|---|---|
| Electron temperature in stria tail in $^{o}K$ | 12,500 | 22,500 | 26,000 | 29,000 | 35,000 |

The decrease of electron energies toward the tail is dictated by inelastic collisions of electrons with gas molecules and selection of high speed electrons by the column walls.

[8] In such discharge conditions, sounding curves possess good linearity. Furthermore, in the discharge, electric oscillations capable of distorting probe characteristics, are almost completely absent.

Furthermore, the thin layer of neutral gas possessing strong dependence of virtual profile for electron collision on electron energy, presents itself in the tail of the stria as a unique filter, singling out in one instance, a flow of fast, and in another - slow electrons. As a result, in certain cases striation damping is promoted at a distance form the site of their formation, and in others, - conversely, sustained striae form.

At low pressure when an appreciable fraction of electrons which entered the head of the stria from the tail of the preceding one, because of few collisions, may generation ionization at great distance from the head of the stria, and electron energy losses are low because of this, conditions are generally not possible which are necessary for striation to form. In fact, experience shows that in all gases, striation disappears when pressure drops.

4. Controlling Formation of Striae

Formation of a potential jump with succeeding formation of a sequence of damping striae must accompany an artificial local drop of charge particle concentration in the uniform column across the anode from the point of concentration decrease. If, however, in the existing layered column there is additional gas ionization in the tail of any stria, due to which concentration of charged particles increases somewhat, then the next (to the anode side) potential jump is thereby attenuated.

Such deliberations were verified experimentally in the following manner. Discharge was produced in hydrogen at $p = 0.1$ mm; $i = 15$ mA in a long discharge tube with diameter 20 mm. Two thin probes were sealed in the tube at considerable distance from each other. So that the first probe (from the cathode side) would fall at the end of the stria tail, a nickel screen with an opening, which could be shifted with an external magnet, was placed in the tube. Striae shifted together with shift of this screen. Figure 10,a shows the discharge pattern when both probes

are disconnected, location of which is indicated by arrows. In fig.10,b, a positive potential is given to the first probe situated in the tail of the stria, relative to adjacent plasma.

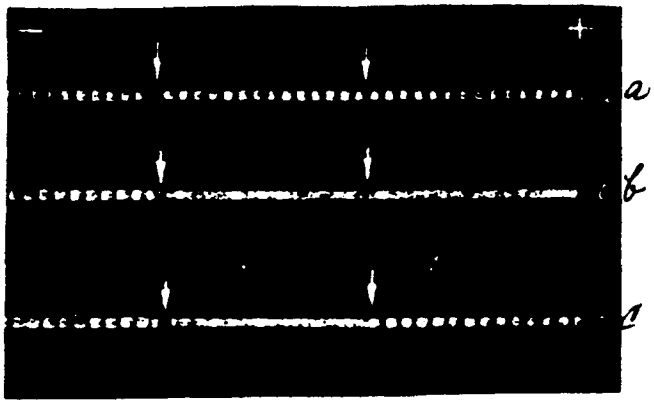


Fig. 10. Annihilation of striae by positively charged probe and their restoration with a negative probe. Arrows show location of probes.

Electrons launched from the plasma to the surface of the probe, produce gas ionization near the probe, and thus, striae completely disappear on the anode side of the probe. It sometimes happens that this disappearance has an apparent nature. Observing discharge with the aid of a rotating mirror demonstrates the presence of pulsing striae at the anode side of the probe. But, such conditions may be selected so that the striae actually disappear. Feed of negative potential to the second probe caused new striation to form in the section from the second probe to the anode (fig. 10,c).

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